Journal of Manufacturing Processes 28 (2017) 285–294

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro

Experimental investigation into micromilling of microgrooves on titanium by electrochemical micromachining

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ARTICLE INFO

Article history:
Received 24 October 2016
Received in revised form 27 April 2017
Accepted 24 June 2017

Keywords:
Microgroove
EMM
Titanium
Layer-by-layer milling
Disc microtool

ABSTRACT

Titanium possesses excellent physical and chemical properties such as higher strength to weight ratio, greater biocompatibility and outstanding corrosion resistance. Therefore, titanium is highly demanding material in aerospace to biomedical applications from macro to micro scale levels. However, machining of titanium in macroscopic or microscopic domain is a complex task either by conventional or nonconventional machining processes. Electrochemical micromachining (EMM) could be one of the alternatives for machining of titanium in microscopic area. The study elaborated in this paper demonstrates successful micromilling of through microgrooves on pure commercial titanium utilizing maskless electrochemical micromachining. Layer-by-layer micromilling strategy has been successfully employed with the help of in-situ fabricated disc shape microtool for micromilling of through microgrooves. Influence of various EMM process parameters such as machining voltage, pulse frequency and microtool feedrate on machining accuracy of through microgrooves were also investigated and established most suitable EMM process parameters for successful micromilling of through microgrooves on pure titanium. This paper also demonstrated successful fabrication of few complex geometry microgrooves by electrochemical micromilling for practical applications. Micromilling of microgrooves on pure titanium by EMM may find vital applications for MEMS, micro fluidics, microsensors, micro engineering and biomedical systems.

1. Introduction

Demand of miniaturization is rapidly increasing in almost all fields, which drives researchers and engineers to explore potentials of various micromachining techniques as well as materials in order to establish novel solutions to microengineering applications. Incorporating advanced materials in micro domain will create larger impact to the functional aspects of microstructures. Titanium is a material known for its versatile physical and mechanical properties such as high strength to weight ratio, high compressive and tensile strength, low density, high fatigue resistance in air and seawater, and exceptional corrosion resistance [1–3]. This made titanium prominent material in a variety of applications such as aerospace, biomedical, sporting goods, marine, military and chemical industries. However, titanium machining either by conventional or non conventional methods is an always a concern to the researchers and engineers due to its poor machinability. In the conventional subtractive machining techniques, problems such as shorter tool life and higher tool wear reported because of higher cutting forces and excessive heat generation due to poor thermal properties of the titanium as well as chatter, deflection and rubbing of cutting tool owing to low modulus of elasticity with its ability to maintain high strength at elevated temperatures [4]. Titanium is very chemically reactive hence; it has a tendency to weld to the cutting tool during machining leading to chipping and premature tool failure [5]. Even in non conventional machining process machining of titanium is an intricate task, Electric Discharge Machining (EDM) and Ultrasonic Machining (USM) has been applied to the machining of titanium and its alloys during recent times. In EDM, formation of thermal stresses in a small heat-affected zone is a serious issue which can lead to micro-cracks, decrease in strength and fatigue life and possibly catastrophic failure of the component [6]. Ultrasonic machining (USM), lower MRR compared with other processes and serious tool wear that usually affects machining precision [7]. Laser beam machining (LBM) can be applied for machining of titanium, but even this process has its own problems of heat affected zone and re-solidification of layers as well as probability of formation of hot spot due to thermal effect [8].

Electrochemical machining (ECM) has proved its compatibility for machining of titanium in macro scale level. In ECM, material removal carried out by anodic dissolution principle hence, this process can machine materials irrespective of their hardness.

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http://dx.doi.org/10.1016/j.jmapro.2017.06.016
1526-6125/

When ECM is employed for fabrication of features in microscale level i.e. microfeatures in the range from 1 to 999 μm then ECM becomes electrochemical micromachining (EMM) [9]. EMM emerged as potential micromachining technology due to its several advantages such as high MRR, enhanced precision and control and environmentally tolerable in addition to that it also machine chemically resistant materials i.e. titanium, stainless steel and super alloys [10]. Therefore, micromachining of titanium by electrochemical process could be one of the competent alternative techniques for machining of titanium. Machining of titanium in macroscopic domain utilizing Electrochemical machining (ECM) has been reported [11,12]. However, in microscopic domain, most of the work has been reported in the area of micropatterns generation intended for surface structuring applications either by electrochemical etching, or electrochemical polishing (EP) [13–16]. All these techniques were utilized expensive and complex sophisticated processes such as through mask electrochemical micromachining (TMEMM) or with confined etchant layer technique or by oxide film laser lithography. But very few or almost no attempts have been reported based on fabrication of complex microfeatures on pure titanium utilizing maskless electrochemical micromachining (EMM). Major challenge in fabrication of microfeatures on titanium is to achieve controlled anodic dissolution of titanium in micro domain by overcoming passivity of oxide layer present on surface of the titanium. Hence, in this paper systematic experimental investigation has been carried out to identify optimum process parameters for generation of microfeatures such as through microgrooves by achieving controlled anodic dissolution of titanium in microscopic level. The work elaborated in this paper also demonstrated layer by layer electrochemical micromilling strategy with the aid of in-situ fabricated cylindrical disc shape microtool for successful micromilling of complex shape through microgrooves utilizing indigenously developed maskless electrochemical micromachining set up.

1.1. *Anodic dissolution of titanium by EMM*

Anodic dissolution of pure titanium utilizing electrochemical micromachining (EMM) is complex task compared to EMM of other metals. Titanium possesses good corrosion resistance because of presence of surface oxide film. This protective tenacious oxide film is formed on the surface of titanium, when titanium is depicted to oxygen containing media such as air, water etc [17]. When titanium undergoes electrochemical actions, the role of transfer of Ti^{2+} and O^{2-} is contribute for development of anodic film. Formation of passive oxide layer on titanium surface during electrochemical process with aqueous environment is initiated by reacting Ti^{2+} with hydroxide ions (OH^-) ionized from aqueous solution. Following electrochemical reactions represents stable titanium oxide (TiO_2) [18].

At the interface of anode workpiece and electrolyte, the reactions taking place are:

$$Ti \rightarrow Ti^{2+} + 2e^- \quad (1)$$

$$Ti^{2+} + H_2O \rightarrow TiO^{2+} + H_2\uparrow \quad (2)$$

The oxocation, TiO^{2+} is acidic in nature and subsequently reacts with OH^- to form stable TiO_2 [19].

Following chemical reaction represent the formation of stable TiO_2:

$$TiO^{2+} + 2OH^- \rightarrow TiO_2 + H_2O \quad (3)$$

Throughout the anodic dissolution process, development of oxide layer with the help of titanium and hydroxide ions has been accelerated by the application of electric field.

This thin oxide film is highly passive in nature, causes anodic dissolution of titanium difficult. The controlled anodic dissolution of titanium is difficult by EMM process parameters generally utilized for micromachining of other metals especially in terms of machining voltage and type of electrolyte due to the presence of passive oxide layer. Hence, to attain uniform transpassive dissolution of titanium, the oxide film that obstructs the controlled dissolution of pure titanium in the passive potential region must lose its passivation phenomenon. Removal of oxide film is possible when the applied potential is adequately high [20]. The passive oxide film develops linearly with potential until a significant value is attained and the breakdown of the film takes place from random pitting at higher current densities and then shape controlled dissolution begins [21]. An additional factor, which plays vital role in rupturing this passive oxide film, is the electrolyte type i.e. Electrolytes containing bromide ions have been effective in breakdown of oxide film [22]. Electrolyte solution includes bromide ions can promote anodic dissolution of titanium with valance of 4 i.e. $Ti \rightarrow Ti^{4+}$ [23]. The use of aqueous based electrolytes for EMM of titanium can create the possibility of formation of passive oxide layer or increase the thickness of already existing oxide film formed due to atmospheric oxygen. Use of aqueous based electrolytes could be altered with non-aqueous based electrolytes to minimize the chances of formation of passive oxide layer [24]. The accuracy of the micro machined product in EMM is highly influenced by process parameters e.g. applied machining voltage, duty ratio, pulse frequency, concentration of electrolyte, inter-electrode gap (IEG) and micro tool feed etc. Therefore, appropriate selection along with controlling of all these EMM parameters play a vital role in attaining the preferred results during titanium micro machining utilizing EMM.

2. Experimental setup

Experimentation for micromachining of titanium has been executed on indigenously developed electrochemical micromachining set up as shown in Fig. 1. The EMM experimental set up consist of different subsystems i.e. mechanical machining unit, desktop computer, DC pulsed power supply, digital storage oscilloscope (Tektronix) as well as measuring microscope etc. Indigenously fabricated electrolyte chamber from Perspex material having work holding arrangement has been employed for the experimentation. Mechanical machining unit includes three linear travel stages designating X, Y, and Z-axis. The stepper motors of each linear stage with resolution of 0.1 μm/step are controlled by CNC controller unit, which is interfaced with desktop computer. Different feeds can provide to all the three stepper motors at a time with the help of position controller software through desktop computer. DC pulsed power supply has been used for generation of required nature of pulse power intended for micro machining operation. Digital storage oscilloscope has been used for observation of pulse waveform. The digital multimeter (Agilant U1252A) was connected in series to the circuit for the measurement of current values. Stereo type microscope (Leica S6D) was used for observation, measuring microscope (Leica DM2500) were utilized for measurement of various criteria of machined microfeature. To augment the supply of electrolyte into the narrow inter electrode gap (IEG) during EMM operation by providing longitudinal vibrations to the microtool, Piezoelectric transducer (PZT) has been utilized.

3. Experimental planning

In order to investigate the influence of various EMM process parameters on various responses such as accuracy of microgroove in terms of width overcut (WOC), length overcut (LOC) and taper, all the experiments were systematically planned and executed by